Improvements of astrometry from ground based observatories

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Introduction

The analysis of planetary satellites or asteroids ground based observations is quite similar. Our first goal was to improve the astrometric reduction for digitized photographic plates in case of too few reference stars and to propose solutions. We here present astrometric techniques used for old observations of the Galilean satellites made with the 26-inch refractor of USNO in Washington DC from 1967 to 1998 (Pascu, 1977, 1979, 1994). We present some solutions that may be applied to asteroids or any small solar system bodies observations. In fact, we were able to determine an observational error and we discuss the expected improvements necessary in the frame of the GAIA FUN SSO program. A real application in the frame of the Gaia program deals with the new analysis of old photographic plate observations.

1. Improvement of the reduction of an image

1.1 *Centroiding each object*

USNO images were analyzed by using a specific process to identify the planet, its satellites and the available reference stars. This process is analog to a pre-reduction and provided the best results (Robert, 2011). All the available stars (depending on the catalog used) are identified and more, those that are not visible with naked-eyes. The issue consists in looking for relevant objects in specific areas before their identification. Four star catalogs can be used: Hipparcos (Perryman et al., 1997), Tycho-2 (Hog et al., 2000), UCAC2 (Zacharias et al., 2004) and UCAC3 (Zacharias et al., 2010). The identification method can be applied with any objects; tests were succesfully performed with USNO Saturn and Mars images, and with OHP Pluto and asteroid images.

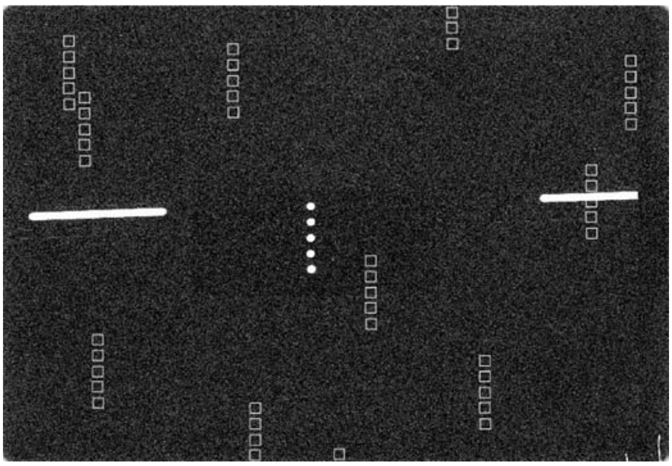

Figure 1: Method to identify relevant objects in an image

The star catalogues

Year	Name	Nb of stars	Mag limit	Accuracy mas	Accuracy pr motions	Origin
1997	Hipparcos	120 000	12.4	< 0.78	< 0.88 m/y	obs. from space
2000	Tycho 2	2 500 000	16	< 60	< 2.5 m/y	from Tycho and 143 sources
1998	USNO A2	526 280 881				
2001	GSC II	19 000 000		360		Schmidt plates
2003	USNO B1	1 billion	21	200		Schmidt plates
2004	UCAC 2	48 000 000	7.5 → 16	20 → 70	1 → 7 m/y	scans
2004	Bright stars	430 000	< 7.5			Hipparcos + Tycho2
2005	Nomad	1 billion				compilation of best entries
2006	Bordeaux	2 970 674	15.4	50 → 70	1.5→6 m/y	+11° > δ > +18°
2003	2MASS	470 000 000	16	60 → 100		Infra red K
2015	GAIA	1 billion	20	< 0.01 mas		obs. from space

Figure 2: Comparison of star catalogs dedicated to astrometry

At the present time, we use to neglect small biases when the error is smaller than the accuracy of the catalog. Mainly when a catalog with a large number of stars is used, the accuracy of that being very poor. This will change when using the Gaia catalog: all small effects should be corrected.

1.2 *Astrometric reduction*

In the case of few available stars, the astrometric reduction is quite different with a common one. We propose that the star $(\alpha,\delta)_c$ equatorial coordinates should be directly corrected for all-known spherical effects, the star $(x,y)_m$ measured coordinates should be corrected for the evaluated instrumental effects, and the astrometric reduction should be realised through the atmosphere so that (α,δ) equatorial coordinates could be deduced from apparent (X,Y) tangential coordinates. Thus the reference stars only provide position, scale and orientation for the field through an adapted $(x,y)_m \mapsto (X,Y)_{m,a}$ model (Robert, 2011):

$$X_{m,a} = \rho\cos\theta \times x_m - (\rho + \varepsilon_1 \sin(\varepsilon_2 t_m + \varepsilon_3))\sin\theta \times y_m + \Delta_x + C_x \times x_m \times (m - m_0)$$
$$Y_{m,a} = \rho\sin\theta \times x_m + (\rho + \varepsilon_1 \sin(\varepsilon_2 t_m + \varepsilon_3))\cos\theta \times y_m + \Delta_y + C_y \times y_m \times (m - m_0)$$

Only 4 parameters are fitted for a minimum of 2 reference stars, the contribution of each plate constant is here separated.

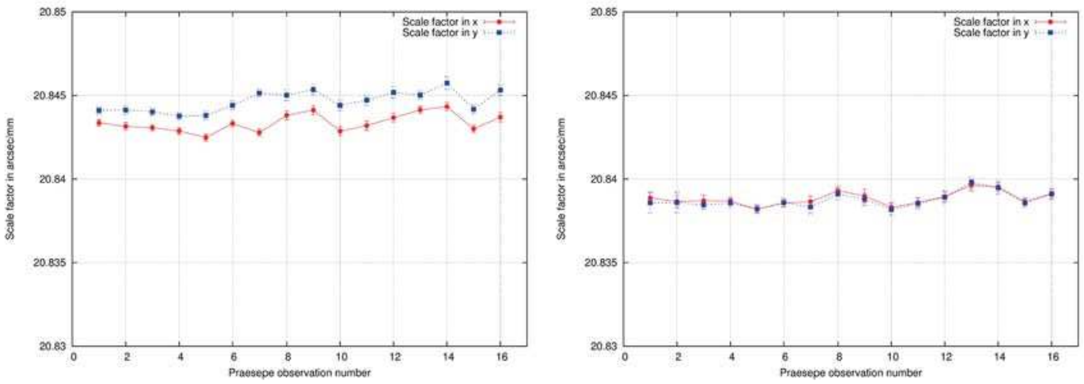

Figure 3: Scale in RA and Dec after correction.

The astrometric method was tested with USNO Galilean observations. As a result, Figure 3 shows on the left the evolution of the scale factors with no corrections applied; on the right the same evolution once the spherical and instrumental corrections are applied to the equatorial and measured star coordinates:

the isotropy of the field is now effective. In conclusion, very small effects may be corrected through a good astrometric modeling of the image.

2. Accuracy and expected improvements

2.1 *Astrometric accuracy*

The final observed position of object is very dependant of the astrometric reduction that may move the objects in the sky. The number and the distribution of the stars in the field must be carefully studied before the reduction.

Exposition		$(O-C)_X$	$(O-C)_Y$
1	(a)	0.060	0.130
	(b)	0.048	0.108
	(c)	0.203	0.188
	(d)	**0.009**	**0.028**
2	(a)	0.059	0.082
	(b)	0.036	0.057
	(c)	0.195	0.139
	(d)	**0.016**	**0.033**
3	(a)	0.096	0.077
	(b)	0.076	0.060
	(c)	0.248	0.125
	(d)	**0.017**	**0.017**
4	(a)	0.098	0.036
	(b)	0.128	0.043
	(c)	0.238	0.066
	(d)	**0.021**	**0.009**

Table 1: Comparison of reduction methods: tangential (O-C)'s in arcsec with secondary PPM catalog 6 stars order 1 (a), 7 stars order 1 (b), 7 stars order 2 (c), and UCAC2 catalog 10 stars order 1 (d).

Table 1 provides the results of the USNO test plate 0216 reduced with four different astrometric methods. Positions determined with our last method are more accurate, the astrometric accuracy is better by a factor between 2 to 15. This shows the interest of new accurate catalogs: Gaia will improve these results again. However the improvement will be limited if we do not improve the astrometric process of observation too.

2.2 *Expected improvements*

The astrometric accuracy depends on many factors and we can expect corresponding improvements in order to provide even more accurate positions:

1. the image pixel sampling → choice of a pixel size depending on the seeing;
2. the centroid of image (trailed images) → use a gaussian fit for the photocenter of punctual sources;
3. the object magnitude → increasing the S/N signal noise ratio;
4. the atmospheric refraction → improving the model of the atmospheric refraction;
5. the sky absorption for moving objects → taking into account the effect for moving object low on the horizon through a photometric monitoring of the exposure;

6. the correction photocentre-centre of mass $\rightarrow$ better correction photocentre to centre of mass by using a recent modeling of the surface of the object.

Conclusion

The astrometric reduction of digitized photographic plates with new tools made necessary to take into account all instrumental errors and all biases. We succeeded in obtaining very good results and we consider that similar corrections should be applied to modern observations, increasing the astrometric accuracy.
In another hand, some observations are difficult to reduce or present some biases. The astrometric positions provided by these observations will not be precise enough in the frame of the Gaia project. Corrections for instrumental errors, for the atmospheric refraction and for the sky absorption should be made at first. More, when using the Gaia catalog for future reductions, all biases must be corrected.

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